View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Ain Shams Engineering Journal (2012) 3, 367–374

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
www.sciencedirect.com

CIVIL ENGINEERING

Fatigue and rutting lives in flexible pavement

Ahmed Ebrahim Abu El-Maaty Behiry *

Highways and Airports Engineering, Engineering Faculty, Civil Department, Minufiya University, Shibeen El-kom City, Egypt

Received 29 September 2011; revised 20 March 2012; accepted 21 April 2012
Available online 12 October 2012

KEYWORDS

Fatigue life;
Rutting life;
Tensile strain;
Compressive strain;
Flexible pavement;
Pavement design

Abstract Flexible pavement is designed based on axle load limits and climatic conditions. The Egyptian code has specified certain load limits that should not be exceeded. The overweight trucks cause severe deterioration to the pavement and thus reduce its life. The study aims at studying the effect of axle load increase, and the variation in pavement modulus, on the overall pavement life. The research uses the BISAR software and the Egyptian environmental and pavement materials conditions to estimate the tensile strains occurring under the asphalt concrete (AC) layer and the compressive strains above the subgrade surface. The results revealed that tensile and compressive strain increased with increasing axle loads and decreased with increasing asphalt layer modulus thus the violating trucks should be unloaded when their weights exceed certain limits. Base thickness and subgrade resilient modulus were the key elements which control the equilibrium between fatigue and rutting lives.

© 2012 Ain Shams University. Production and hosting by Elsevier B.V. All rights reserved.

1. Introduction

During the last few years excessive damages were observed on several highways, mostly on high volume major roads. The reasons behind can be observed: mixture design, high temperature in summer, change in traffic load, etc. In Egypt, there are many types of heavy vehicles of 6-axles of total weight ranging over from 42 to 52 ton. These heavy vehicles have a bad effect on pavement responses [1].

A field observation in Egypt for evaluation of pavement surface conditions of Egyptian road's network showed that rutting and fatigue cracking are considered the most important distresses surveyed due to high severity and density levels, and consequently, their high effects upon the pavement condition. Flexible pavements should be designed to provide a durable, skid resistance surface under in-service conditions. Moreover, it is essential to minimize cracking and rutting in flexible pavement layers. To fully utilize each pavement material in an economic design a pavement should generally have reasonably balanced design between the rutting and fatigue modes of distress. The increased rutting or decreased fatigue life of the flexible pavements may be attributed to the shortcomings of the application of flexible pavement analysis and the absence of attention to identify the pavement components that achieve a balanced section which gives equal pavement lives with respect to rutting and fatigue [1].

In pavement analysis loads on the surface of the pavement produce, two strains which are believed to be critical for design

Abbreviations: d, layer thickness; *E*, elastic modulus; μ, Poisson's ratio.

* Mobile: +20 0183961800.
E-mail address: maaty5000@yahoo.com

Peer review under responsibility of Faculty of Engineering, Ain Shams University.

ELSEVIER Production and hosting by Elsevier

2090-4479 © 2012 Ain Shams University. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.asej.2012.04.008

Table 1 Fatigue model coefficients based on different agencies.

No.	Organization	$f1$	$f2$	$f3$	Ref.
1	Asphalt Institute	0.0795	3.291	0.854	[1]
2	Shell Research	0.0685	5.671	2.363	[3]
3	US Army Corps of Engineers	497.156	5	2.66	[1]
4	Belgian Road Research Center	4.92E−14	4.76	0	[4,5]
5	Transport and Road Research Laboratory	1.66E−10	4.32	0	[4,5]
6	Federal Highway Administration	0.1001	3.565	1.474	[6]
7	ILLINOIS Department of Transportation	5.00E−06	3	0	[6]
8	Austin Research Engineers (ARE)	0.4875	3.0312	.06529	[7]

Table 2 Rutting model coefficients based on different agencies.

No.	Organization	$f3$	$f4$	Ref.
1	Asphalt Institute	1.365E−09	4.477	[1]
2	Shell Research	6.15E−07	4	[3]
3	US Army Corps of Engineers	1.81E−15	6.527	[3]
4	Belgian Road Research Center	3.05E−09	4.35	[4]
5	Transport and Road Research Laboratory	1.13E−06	3.75	[4]

purposes. These are: the horizontal tensile strain (εt) at the bottom of the asphalt layer and the vertical compressive strain (εv) at the top of the subgrade layer. If the horizontal tensile strain (εt) is excessive cracking of the surface layer will occur, and the pavement distresses due to fatigue. If the vertical compressive strain (εv) is excessive, permanent deformation occurs on the surface in the pavement structure from overloading the subgrade, and the pavement distresses due to rutting [1]. Several fatigue and rutting models have been developed to relate the asphalt modulus and/or the measured strains to the number of load repetitions to pavement failure. Most of the fatigue failure models take the following form [2]:

$$\mathrm{Nf} = f1\varepsilon t^{-f2}E1^{-f3} \tag{1}$$

While the rutting models usually take the following form:

$$\mathrm{Nr} = f4(\varepsilon v)^{-f5} \tag{2}$$

where Nf is the allowable number of load repetitions to prevent fatigue cracking from reaching a certain limit (10–20% of the pavement surface area); Nr the allowable number of load repetitions to prevent rutting from reaching a certain limit (0.5 in.); εt: the tensile strain on the bottom of the asphalt layer; εv the compressive vertical strain on the surface of subgrade; $E1$ the elastic modulus of the asphalt layer; and $f1$, $f2$, $f3$, $f4$, $f5$ is the regression coefficients.

The values of the regression coefficients shown in the previous equations usually vary according to material type, environment, traffic conditions and the failure limits specified by the agency. According to references [1,3–7], regression coefficients values, in English units, based on different agencies are presented in Tables 1 and 2.

2. Problem statement and study objective

Flexible pavements, in Egypt, are designed according to the AASHTO design guide. The axle load limits are specified by the Egyptian General Authority of Highway and Bridges (EGAHBs). The maximum allowed axle load for single axle dual tire was 10 tons. Due to the construction of the new international, coastal highway and the expected international trucks using that highway, the HGAHBs proposed increasing the axle load limits. Furthermore, many trucks throughout the country violate the specified load limits by carrying additional weights to decrease the transportation cost. Those overweight trucks cause severe deterioration to the pavement. The Egyptian authorities generally charges the violating trucks a penalty based on their weights. Such penalty could be very small compared to the damage occurring to the pavement based on these over weights. Furthermore, some trucks may carry huge weights that the pavement may not support, so unloading such trucks could be the suitable solution rather than paying few amounts of money and deteriorating the pavement. This study aims at studying the effect of axle load increase, pavement layers thicknesses increase and the variation in temperature and elastic modulus of pavement layers, on the overall pavement life.

3. Research approach

The BISAR computer program was used to calculate the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade soil. These computed strains are incorporated in the fatigue cracking and rutting models to estimate the pavement life for different axle weights. Different axle loads are considered in this research; the standard; the previous maximum allowed axle load in Egypt, 10 tons, the new proposed axle load, 13 tons, and additional smaller and larger axle loads (from 6 to 30 tons). The assumed axles are the most common, more critical, ones having two sets of dual tires with 120 psi (827 kPa) tire pressure and 12 in. (30 cm) dual spacing.

3.1. Layers' properties

The elastic modulus of the asphalt concrete (AC) layer is highly affected by pavement temperature, where, the modulus

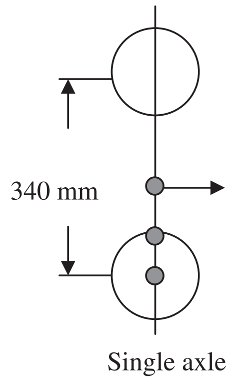

Figure 1 Geometry of axle's configuration.

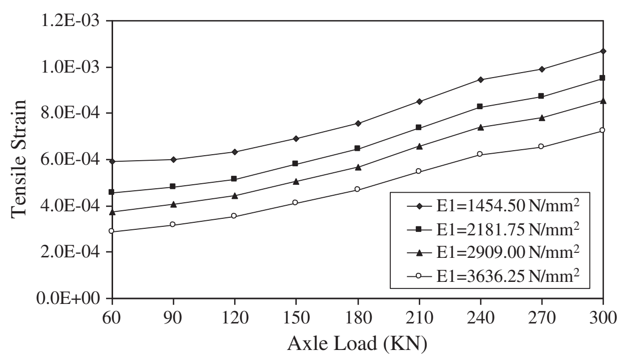

Figure 2a Tensile strain at the bottom of asphalt layer.

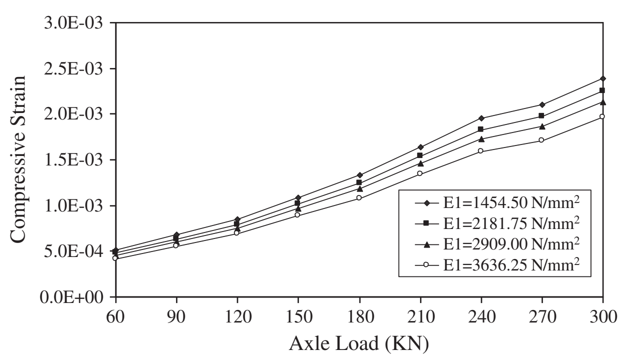

Figure 2b Compressive strain at the top of subgrade.

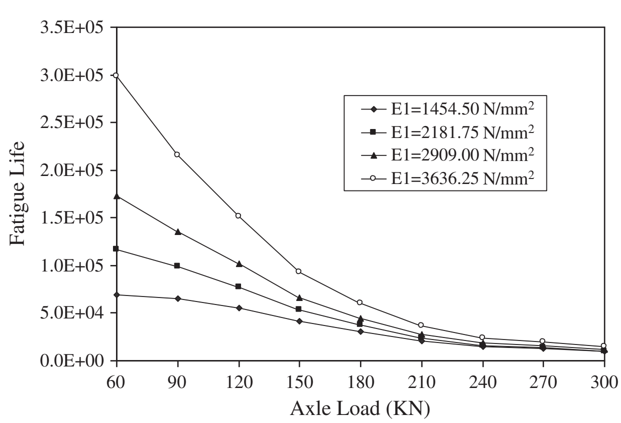

Figure 3a Fatigue life.

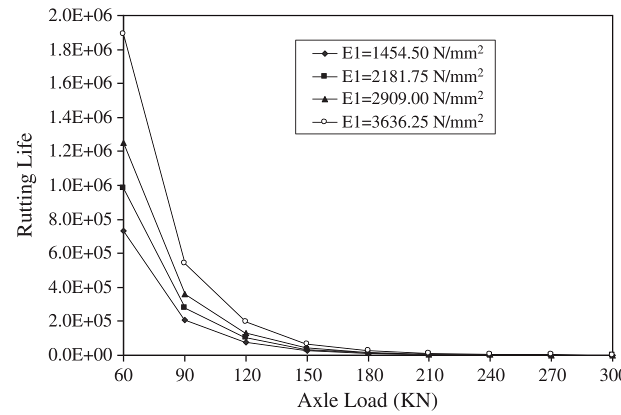

Figure 3b Rutting life.

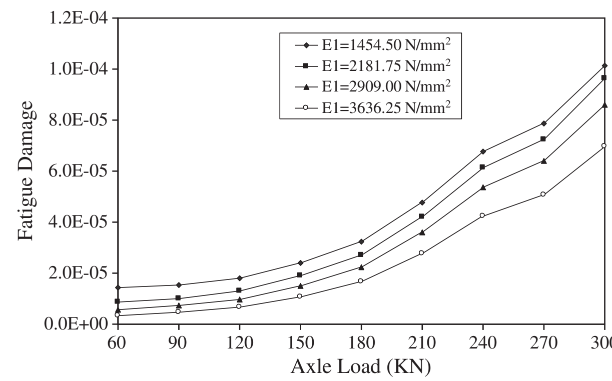

Figure 4a Fatigue damage ratio.

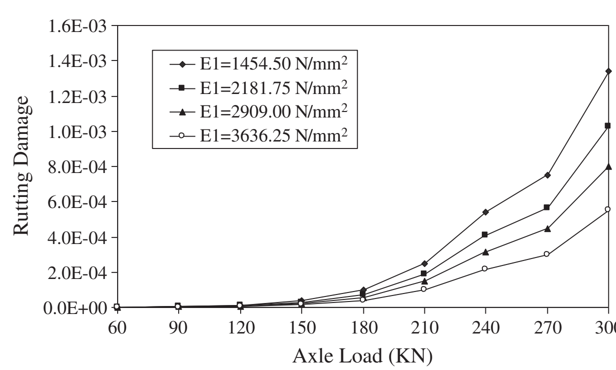

Figure 4b Rutting damage ratio.

decreases as the temperature increases. Elastic modulus of asphalt layer ($E1$) could be determined as a function of pavement temperature according to the following equation [1]:

$$E1 = 15000 - 7900\log(t) \tag{3}$$

where $E1$ is the elastic modulus of asphalt layer (N/mm^2) and t is the pavement temperature (°C).

The pavement temperature in Egypt ranges from 10 °C and 50 °C. Therefore, different AC layers' modulus are considered in this study to represent different climatic conditions from the strongest (greatest) AC modulus during winter to the weakest (smallest) modulus during summer. The values of surface elastic modulus ($E1$) range according to Eq. (3) from 1454.5 to

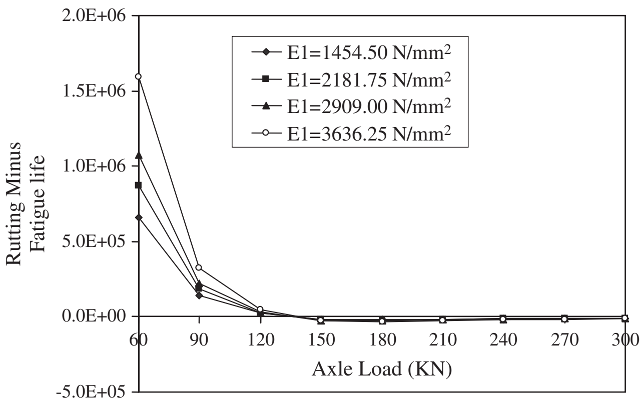

Figure 5 Difference between rutting and fatigue lives.

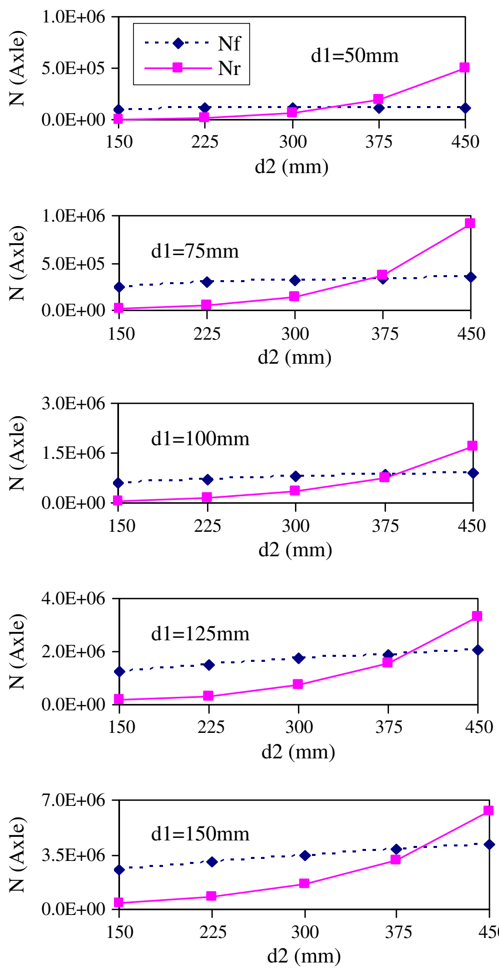

Figure 6a Effect of $d1$ on $d2$ in fatigue and rutting lives.

3636.25 N/mm^2. Different subgrade modulus ($E3$) (from 29 to 87 N/mm^2), are considered corresponding to subgrade CBR values of 3 and 8.5 respectively. The modulus of the aggregate base layers ($E2$) assumed to be ranged (from 87 to 261 N/mm^2). The layers' thicknesses are the typical cross sections commonly used in Egypt, which is 10 cm (AC) layer (range from 5 to 15 cm) and 40 cm of the base layer (range from 15

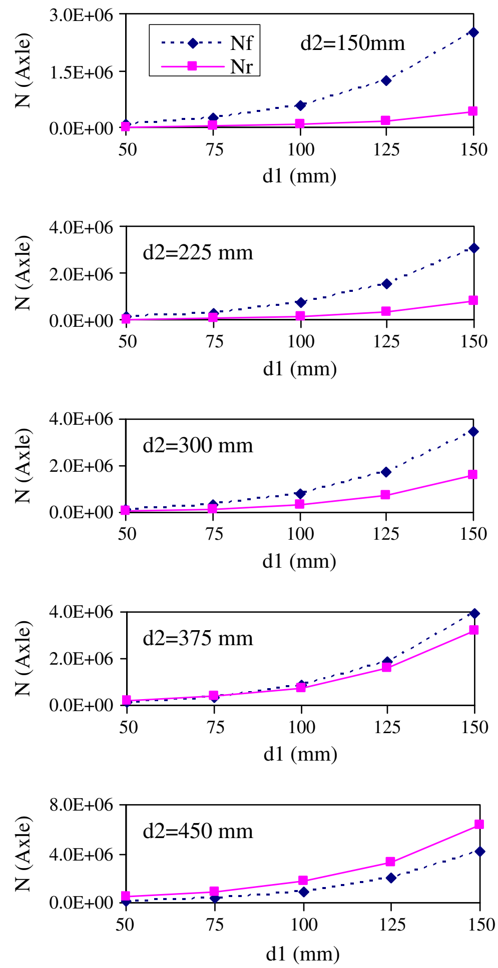

Figure 6b Effect of $d2$ on $d1$ in fatigue and rutting lives.

to 45 cm). The assumed axle loads' values range from 60 kN to 300 kN with contact tire pressure 0.5 N/mm^2.

3.2. Fatigue life prediction

The relationship between fatigue failure of asphalt concrete and tensile strain (εt) at the bottom of asphalt layer was represented by Philip et al. [8] by using the number of load repetitions in the following form:

$$\mathrm{Log(Nf)} = 16.664 - 3.291\log(\varepsilon t \times 10^6) - 0.854\log(E1) \quad (4)$$

where Nf is the number of load applications to fatigue cracking over 10% of the wheel path area; εt the horizontal tensile strain repeatedly applied at the bottom of the asphalt layer; and $E1$ is the stiffness modulus for the asphalt layer (N/mm^2).

3.3. Rutting life prediction

The relationship between rutting failure of asphalt concrete and compressive strain (εv) at the top of subgrade was represented by Oglesby and Hicks [9] by using the number of load repetitions in the following form:

$$\mathrm{Nr} = 1.365 \times 10^{-9}(1/\varepsilon)^{4.477} \quad (5)$$

where Nr is the number of load applications to limit rutting and εv is the vertical compressive strain, at the top of subgrade.

3.4. Damage prediction

In the present study, the prediction of pavement life for fatigue and rutting is based on the cumulative damage concept in which a damage factor is defined as the damage per pass caused to a specific pavement system by the load in question [10]. The damage (Di) caused by each application of a single axle load at any season can be given by:

$$\mathrm{Di} = 1/\mathrm{Ni} \tag{6}$$

where Di is the cumulative damage and Ni is the minimum number of load repetitions required to cause either fatigue (Nf) or rutting (Nr) failure.

The total number of load repetitions that are allowed over the pavement lifetime can be determined when total cumulative damage (Di) reaches one. Therefore, Eqs. (4) and (5) can then be solved for the total allowable number of load applications required to cause either fatigue or rutting failures over the pavement lifetime.

3.5. Points used for determination of maximum strains

The geometry of axle structure along with the locations for the determination of maximum strains is illustrated in Fig. 1 [11].

4. Results and discussions

Multilayer elastic analysis is performed using the BISAR software. The different variables discussed in the previous section are considered. The resulting pavement strains, damage and pavement lives (number of load repetitions to failure) are investigated. The following sections discuss the outcomes of these results.

4.1. Effect of excess axle loads and asphalt layer elastic modulus on pavement strains

Figs. 2a and 2b present the relationship between tensile strain on the bottom of asphalt layer and the compressive strain on the top of subgrade soil versus axle load for different asphalt layer elastic modulus. The figures show that the tensile and compressive strain increase with increasing the axle load. Moreover, Figs. 2a and 2b show that the increase in the elastic modulus of asphalt layer leads to a decrease in pavement strains.

4.2. Effect of excess axle loads and asphalt layer elastic modulus on pavement fatigue and rutting lives

Fatigue and rutting lives are calculated according to Eqs. (4) and (5). Figs. 3a and 3b present the fatigue and rutting lives

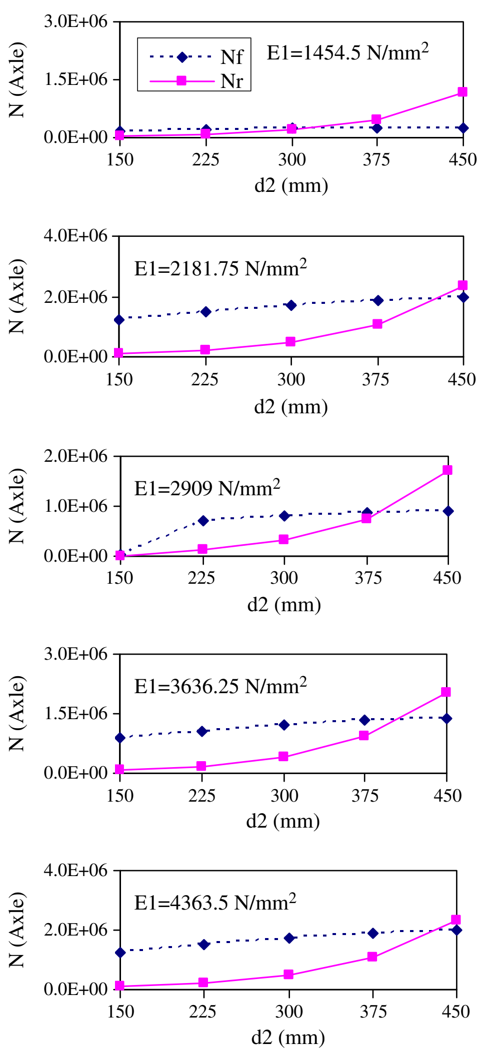

Figure 7a Effect of $E1$ on $d2$ in fatigue and rutting lives.

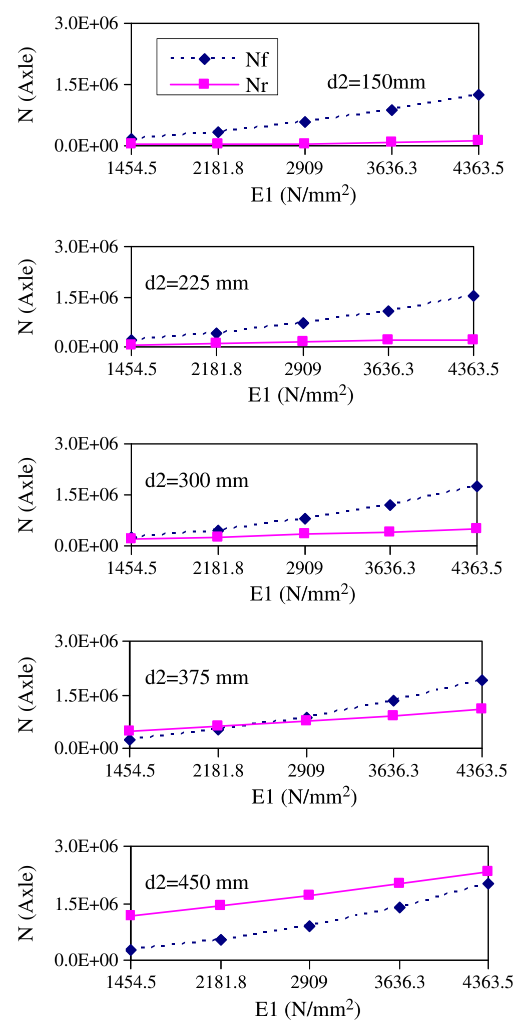

Figure 7b Effect of $d2$ on $E1$ in fatigue and rutting lives.

versus axle loads for different asphalt layer elastic modulus. The figures show that both fatigue and rutting lives decrease dramatically with increasing the axle load, especially at the axle load exceeds 150 kN for fatigue life and 120 kN for rutting life. The figures also show that the variation in the asphalt layer elastic modulus is more significant with fatigue than rutting life, especially at high axle loads.

4.3. The pavement design life

The pavement design life is the minimum number of load repetitions required to cause either fatigue or rutting failure [11]. From Figs. 3a and 3b it can be concluded that the pavement design life is generally governed by fatigue failure with smaller axle loads (less than 150 kN), and by rutting failure with greater axle loads.

4.4. Effect of excess axle loads and asphalt layer elastic modulus on pavement damage ratio

Damage ratio for both fatigue and rutting lives are calculated according to Eq. (5). The fatigue and rutting damage ratios according to axle load are presented in Figs. 4a and 4b at different asphalt layer elastic modulus. From these figures, it can be concluded that the fatigue damage generally increases in an increasing rate (diverging) with increasing the axle load. While the rutting damage increases with a decreasing rate (converging). Furthermore with increasing asphalt layer elastic modulus the fatigue and rutting damage decrease.

4.5. Optimum axle load causing both fatigue and rutting failures

As previously explained, the pavement design life is the minimum number of load repetitions required to cause either fatigue or rutting failure as given by Eqs. (3) and (4). Therefore, the optimum axle load that causes both fatigue and rutting failures, at the same time, can be achieved when the difference between rutting and fatigue lives is zero.

Fig. 5 presents the difference between rutting and fatigue lives. From this Figure, it can be concluded that the optimum axle load causing both fatigue and rutting failures at the same time is 135 kN for AC modulus ranging from 1454.5 to 3636.25 N/mm^2 (summer and winter) respectively. Moreover, for axle load less than (135 kN), the difference between rutting

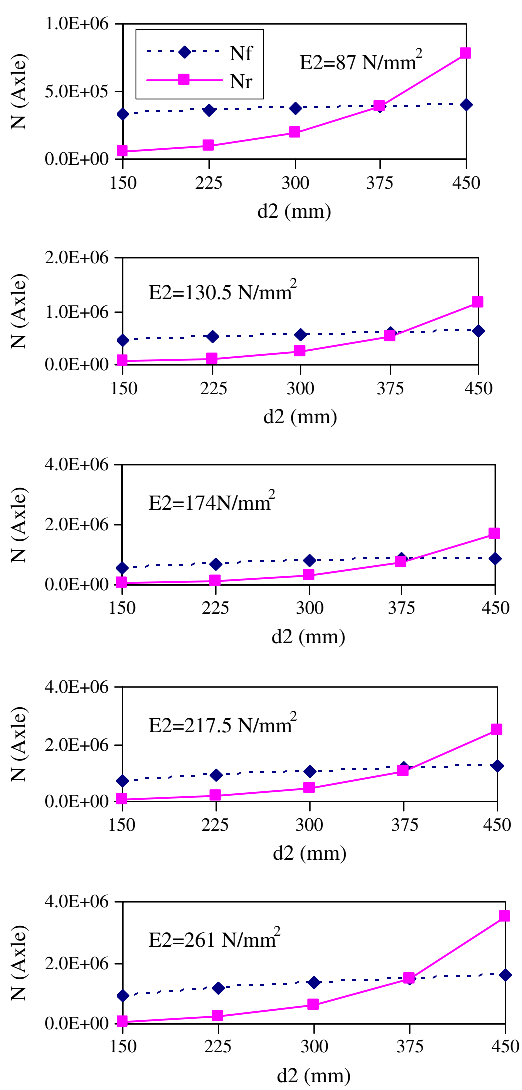

Figure 8 Effect of $E2$ and $d2$ on fatigue and rutting lives.

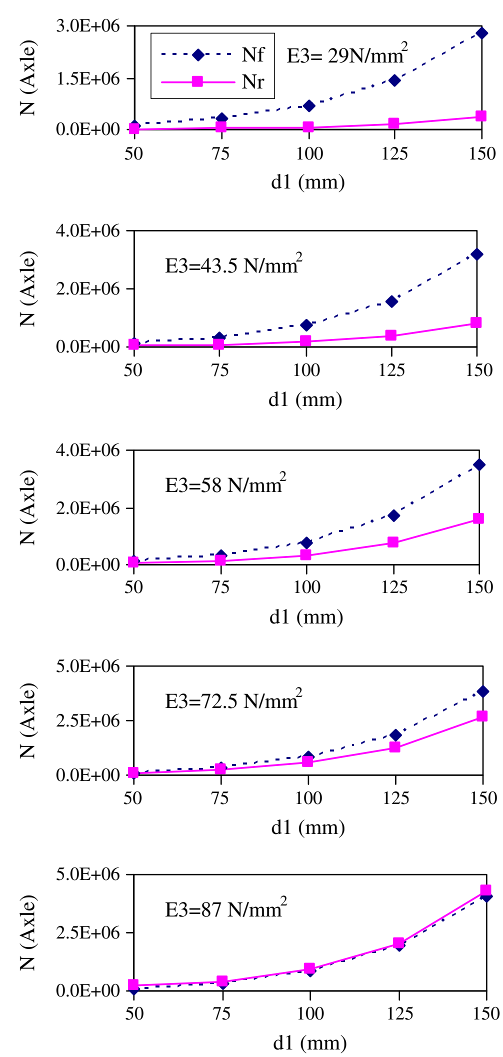

Figure 9a Effect of $E3$ on $d1$ in fatigue and rutting lives.

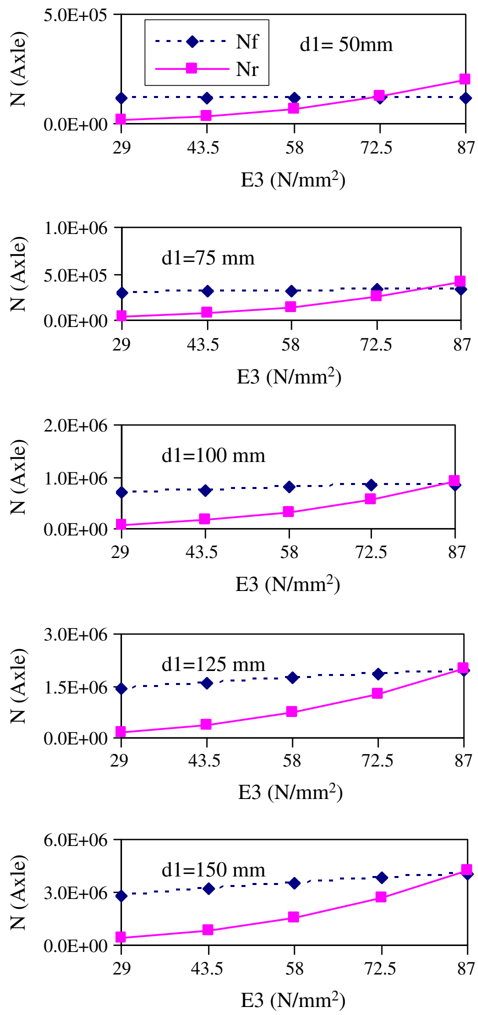

Figure 9b Effect of $d1$ on $E3$ in fatigue and rutting lives.

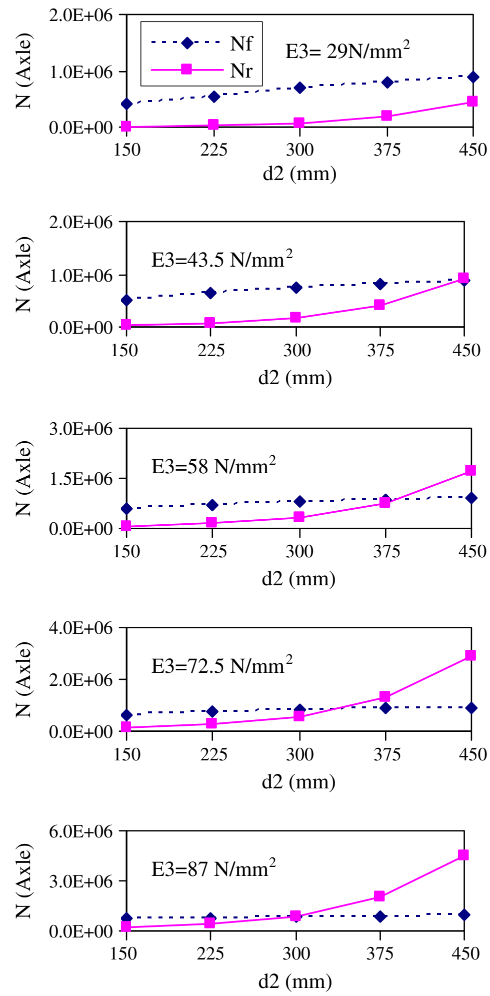

Figure 10 Effect of $E3$ and $d2$ on fatigue and rutting lives.

and fatigue lives is positive thus, the pavement failure is mostly occurred by fatigue (rutting life is greater than fatigue life). On the other hand, for axle load more than (135 kN), the difference between rutting and fatigue lives is negative therefore, the pavement failure is mainly occurred by rutting (rutting life is less than fatigue life).

4.6. Obtaining balanced section between fatigue and rutting lives

Figs. 6a and 6b show the effect of $d1$ and $d2$ on pavement fatigue (Nf) and rutting (Nr) life. It can be considered that Nf has no sensitivity with the variation of $d2$, compared with Nr which is obviously increases as $d2$ increases. Moreover, both Nf and Nr have a good sensitivity with the variation of $d1$ specially at base thickness ($d2$) thicker than 300 mm. The balanced sections between fatigue and rutting lives are achieved at $d2$ = 300–375 mm for all values of $d1$.

As shown in Figs. 7a, 7b and 8, Nr increases as $d2$ increases at all values of $E1$ and $E2$. The increase of $E1$ or $E2$ has not obvious effect on the Nr values at base thickness thinner than 300 mm, thicker thickness lead to obvious increase in Nr values. With respect to Nf, it has no sensitivity with the variation of $d2$ at all values of $E1$ and $E2$ while has a good sensitivity with the variation of $E1$and $E2$ at all values of $d2$. The balanced sections are achieved at $d2$ = 375 mm for all values of $E1$ and $E2$. Furthermore, Fig. 7b shows that the fatigue life increases with a higher rate at greater AC modulus. This would be reasonable since the pavement behaves as an elastic material with greater AC modulus (lower pavement temperature), while behaves as a plastic material with smaller AC modulus (higher pavement temperature).

Figs. 9a, 9b and 10 show the effect of $d1$, $d2$ and $E3$ on Nf and Nr. It can be observed that Nr obviously increases as $d1$, $d2$ and $E3$ increase. With respect to Nf, it has no sensitivity with the variation of $d2$ or $E3$, and a good sensitivity with the variation of $d1$. The figures also show that the balanced section is achieved for all values of $d1$ at $E3$ equal 72.5–87 N/mm^2. Generally, it can be concluded that $d2$ and $E3$ are the key elements which control the equilibrium between Nf and Nr. For obtaining balanced pavement sections, it is preferable to use $d2$ = 375 mm with $E3$ = 87 N/mm^2, $d2$ = 300 mm with $E3$ = 72.5 N/mm^2, $d2$ = 375 mm with $E3$ = 58 N/mm^2 and $d2$ = 450 with $E3$ = 43.5 N/mm^2. Along with $d1$ = 100 mm, $E1$ = 2909 N/mm^2 and $E2$ = 174 N/mm^2.

5. Conclusions

Based on the pavement temperature in Egypt, this study is achieved using the elastic modulus for surface layer ($E1$) ranged from 1454.5 to 3636.25 N/mm^2. According to the methodology and analysis of results for this study, the following conclusions are drawn:

1. Tensile and compressive strain increased with increasing axle loads and decreased with increasing asphalt layer elastic modulus. Furthermore, fatigue and rutting lives decrease dramatically with increasing the axle load, especially after the axle load exceeds 150 kN for fatigue life and 120 kN for rutting life.
2. The fatigue damage generally increases in an increasing rate with increasing the axle load. While the rutting damage increases with a converging rate. Furthermore with increasing asphalt layer elastic modulus the fatigue and rutting damage decrease
3. Fatigue life has no sensitivity with the variation of base thickness compared with rutting life, which is high sensitive. While both fatigue and rutting lives have a good sensitivity with the variation of surface thickness specially at base thickness thicker than 300 mm.
4. The increase of elastic modulus of asphalt or base layers has not obvious effect on the rutting life at base thickness thinner than 300 mm, thicker thickness lead to obvious increase in Rutting life. With respect to fatigue life, it has no sensitivity with the variation of base thickness while has a good sensitivity with the variation of surface modulus or base modulus at all values of base thickness.
5. The optimum axle load causing both fatigue and rutting failures at the same time is about 135 kN. Thus, the maximum allowable axle load should not exceed 135 kN because it will cause a quick deterioration to the pavement, especially during summer season. Moreover, base thickness $d2$ and subgrade elastic modulus $E3$ are the key elements which control the equilibrium between rutting and fatigue life.
6. The pavement design life is generally governed by fatigue failure with smaller axle loads (less than 150 kN) and by rutting failure with greater axle loads.

References

[1] Abdel-Motaleb M. Flexible pavement components for optimum performance in rutting and fatigue. Zagazig Univ J 2009.
[2] Mathew Tom V, Krishna Rao KV. Introduction to transportation engineering. Press; 2009, p. 27.1–8 [National Programme on Technology Enhanced Learning, India, May, 2009, chapter 27].
[3] Li Chi-Wei. Damage assessment for pavement under repeated loads, M.Sc. thesis in Civil Engineering, Civil Engineering Research Institute, National Central University, China; 2006.
[4] Huang Yang H. Pavement design and analysis. 2nd ed. United States of America: University of Kentucky; 2004.
[5] Carpenter Samuel H. Fatigue performance of IDOT mixtures. Illinois Center for Transportation, Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign; July, 2006.
[6] Ker Hsiang-Wei, Lee Ying-Haur, Wu Pei-Hwa. Development of fatigue cracking performance prediction models for flexible pavements using LTPP data base. In: 86th Annual transportation research board meeting, Washington, DC; January, 2007.
[7] Priest AL. Calibration of fatigue transfer functions for mechanistic-empirical flexible pavement design, M.Sc. thesis, in Civil Engineering, Auburn University, Auburn, USA; 2005.
[8] Owende Philip MO, Hartman Anton M, Ward Shane M, Gilchrist Michael D, O'Mahony Michael J. Minimizing distress on flexible pavements using variable tire pressure. J Transport Eng 2001 [May–June].
[9] Oglesby Clarkson H, Hicks R Gray. Highway engineering. 4th ed. New York: Jon Wiley & Sons; 1982.
[10] Salem HMA. Effect of excess axle weights on pavement life. Emir J Eng Res 2008;13(1).
[11] Abdel-Motaleb ME. Impact of high pressure truck tires on pavement design in Egypt. Emir J Eng Res 2007;12(2).

Ahmed Ebrahim Abu El-Maaty Behiry is a Lecturer in the department of Civil Engineering, Faculty of Engineering, Shebin El-Kom, Minoufiya University, Egypt. He received his Ph.D. in Civil Engineering from Minoufiya University, Egypt., in 2007. His fields of interest include highway structure design, consistency of soil reinforcement, concrete pavement, finite elements analysis, fundamentals of geotechnical engineering and traffic performance analysis.